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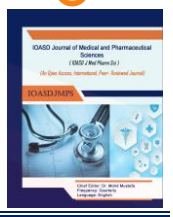

Occult Hematopoietic Malignancies: Pathophysiology, Clinical Presentation, and Prognostic Implications

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ABSTRACT

Occult hematopoietic malignancies are a subset of blood cancers that evade conventional diagnostic methods, often presenting with minimal or non-specific clinical features. These hidden neoplasms, including early-stage leukemias and lymphomas, pose significant challenges due to their potential for rapid progression and transformation into aggressive disease. Advances in molecular diagnostics, immunophenotyping, and imaging have improved detection of subclinical malignancies, revealing complex interactions between malignant clones and the bone marrow microenvironment. This narrative review synthesizes current insights into the pathophysiology, clinical presentation, and prognostic implications of occult hematopoietic malignancies. Emphasis is placed on emerging diagnostic strategies, risk stratification, and the clinical significance of early detection in guiding therapeutic decisions and improving patient outcomes.

Keywords: occult hematopoietic malignancy, minimal residual disease, bone marrow microenvironment, diagnostic biomarkers, prognostic outcome.

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ABBREVIATIONS

ASXL1 – Additional Sex Combs-Like 1
CHIP – Clonal Hematopoiesis of Indeterminate Potential
CLL – Chronic Lymphocytic Leukemia
CT – Computed Tomography
DNMT3A – DNA Methyltransferase 3 Alpha
FLC – Free Light Chain
ICUS – Idiopathic Cytopenias of Undetermined Significance
IDH1/2 – Isocitrate Dehydrogenase 1/2
LDH – Lactate Dehydrogenase
MBL – Monoclonal B-cell Lymphocytosis
MGUS – Monoclonal Gammopathy of Undetermined Significance
MRI – Magnetic Resonance Imaging
NGS – Next-Generation Sequencing
PET-CT – Positron Emission Tomography–Computed Tomography
RUNX1 – Runt-Related Transcription Factor 1
SF3B1 – Splicing Factor 3B Subunit 1
TET2 – Tet Methylcytosine Dioxygenase 2
TP53 – Tumor Protein p53
VAF – Variant Allele Frequency

INTRODUCTION

Hematopoietic malignancies comprise a diverse group of disorders arising from clonal transformation of myeloid or lymphoid progenitor cells. While overt leukemias and lymphomas are often recognized through characteristic clinical symptoms and laboratory abnormalities, a subset—occult hematopoietic malignancies—remains clinically silent or minimally symptomatic. These early-stage or subclinical malignancies may persist undetected for months or even years, presenting only with subtle hematologic changes or incidental findings. Despite their hidden nature, occult malignancies carry significant clinical implications, including the potential for rapid progression, systemic complications, and transformation into more aggressive disease phenotypes [1-2]. The pathogenesis of these malignancies is complex, involving a combination of genetic, epigenetic, and microenvironmental factors. Somatic mutations, chromosomal abnormalities, and epigenetic dysregulation drive clonal expansion, often before overt hematologic derangements become evident.

The bone marrow microenvironment further influences disease dynamics, providing survival and proliferative signals that support malignant clones while simultaneously suppressing immune detection. This interplay contributes to the "silent" course observed in occult disease, delaying clinical recognition and therapeutic intervention [3-4].

Clinically, occult hematopoietic malignancies may manifest with mild cytopenias, vague systemic symptoms such as fatigue or low-grade fever, or be detected incidentally during routine laboratory evaluations or imaging performed for unrelated reasons. Such non-specific presentations challenge conventional diagnostic approaches, necessitating the integration of advanced molecular and immunologic techniques for early detection. Emerging tools, including next-generation sequencing (NGS), multiparametric flow cytometry, and minimal residual disease (MRD) assessment, now enable the identification of malignant clones at subclinical levels, facilitating risk stratification and early intervention [5]. Early recognition not only informs surveillance strategies but also allows clinicians to anticipate disease progression, optimize therapeutic timing, and potentially prevent overt transformation. This narrative review aims to provide a comprehensive synthesis of current knowledge regarding the pathophysiology, clinical presentation, and prognostic significance of occult hematopoietic malignancies, highlighting advances in diagnostic strategies and the clinical value of early detection [6-7].

AIM

The aim of this narrative review is to provide a comprehensive synthesis of current knowledge on occult hematopoietic malignancies, focusing on their pathophysiology, clinical presentation, diagnostic strategies, and prognostic implications. Specifically, the review seeks to:

1. Examine the molecular, genetic, and microenvironmental mechanisms underlying occult hematopoietic malignancies.
2. Characterize the subtle clinical features and laboratory findings that may indicate early-stage or subclinical disease.
3. Highlight emerging diagnostic approaches, including molecular, immunophenotypic, and imaging modalities, for early detection and minimal residual disease assessment.
4. Assess the prognostic significance of occult disease, including risk factors for progression and strategies for risk-adapted surveillance and intervention.
5. Identify gaps in current understanding and future directions for research and clinical management.

METHODS

This narrative review was conducted through a comprehensive and systematic survey of the existing literature on occult hematopoietic malignancies. Relevant studies were identified using electronic databases including PubMed, Scopus, Web of Science, and Google Scholar, covering publications up to 2025. The search strategy combined keywords and Medical Subject Headings (MeSH) terms related to:

- "occult hematopoietic malignancy"
- "minimal residual disease"
- "bone marrow microenvironment"
- "early leukemia"
- "early lymphoma"
- "diagnostic biomarkers"
- "prognostic outcomes"

Eligible studies included original research articles, reviews, meta-analyses, and clinical guidelines focusing on the pathophysiology, clinical presentation, diagnostic approaches, and prognostic implications of occult hematologic malignancies. Articles not available in English or lacking full-text access were excluded.

Data extraction emphasized key findings regarding genetic and molecular mechanisms, immunologic and microenvironmental influences, clinical manifestations, diagnostic modalities—including flow cytometry, molecular assays, imaging, and minimal residual disease assessment—and prognostic factors. The findings were synthesized qualitatively to provide a narrative overview, with attention to emerging diagnostic technologies, clinical relevance, and areas for future research. This methodological approach allowed for an integrative perspective on occult hematopoietic malignancies, emphasizing translational relevance and clinical applicability.

Pathophysiology

The pathophysiology of occult hematopoietic malignancies reflects a gradual and often silent evolution from normal hematopoiesis to measurable but clinically inconspicuous clonal disease. The earliest events typically arise in hematopoietic stem or progenitor cells that acquire somatic mutations conferring selective growth advantages. These mutations—most commonly involving epigenetic regulators such as *DNMT3A*, *TET2*, and *ASXL1* in myeloid precursors or immunoglobulin gene rearrangements, *NOTCH1*, and *TP53* alterations in lymphoid cells—do not immediately result in overt malignancy. Instead, they initiate a subtle clonal expansion that coexists with polyclonal hematopoiesis, creating a mosaic of genetically distinct cell populations within the bone marrow [8-10].

As these mutated clones gain a survival or proliferative edge, they gradually outcompete normal progenitors. This competitive advantage is amplified by microenvironmental changes within the bone marrow niche. Stromal cells, inflammatory cytokines, and altered chemokine signaling reshape the marrow into a milieu that inadvertently supports the persistence of abnormal

clones. Chronic inflammation, in particular, is increasingly recognized as a driving force that fuels clonal dominance. Pro-inflammatory mediators such as IL-6, TNF-α, and interferons promote oxidative stress and DNA damage, thereby accelerating the acquisition of additional mutations while simultaneously suppressing immune surveillance. Over time, the immune system becomes less capable of identifying and eliminating emerging malignant cells, allowing silent clonal expansions to stabilize and grow [11-13].

Despite the presence of these pathogenic mechanisms, many occult hematopoietic malignancies initially induce only minor disruptions in blood formation. The marrow may exhibit subtle inefficiencies—slightly impaired erythropoiesis, mild cytopenias, or skewed lineage maturation—yet these changes are often too minimal to trigger clinical suspicion. Nonetheless, microscopic and molecular analyses reveal early indicators of dysfunction, such as increased apoptosis of normal progenitors, dysplastic features in myeloid cells, or minor aberrations in lymphoid differentiation. These biologic fingerprints represent the earliest detectable signs of malignant potential [14-15]. The transition from a silent clonal disorder to a clinically significant malignancy usually requires the accumulation of secondary genetic or epigenetic hits. These additional alterations may promote resistance to apoptosis, enhance proliferative signaling, or impair DNA repair mechanisms, ultimately tipping the balance toward uncontrolled growth. In some cases, extrinsic factors such as immune senescence, metabolic stress, or environmental exposures accelerate this progression. In others, the malignant clone remains stable for years, constrained by intrinsic limitations or host factors that prevent full transformation (Table 1) [16].

Table 1: Pathophysiology of Occult Hematopoietic Malignancies

Mechanism	Description	Clinical/Relevance Implications
Genomic and Epigenetic Alterations	Somatic mutations (e.g., *DNMT3A, TET2, ASXL1*), chromosomal abnormalities, and epigenetic dysregulation drive clonal expansion while maintaining subclinical disease.	Initiates pre-leukemic or pre-lymphomatous clones; can progress to overt malignancy over time.
Bone Marrow Microenvironment	Stromal cells, extracellular matrix, and signaling pathways (CXCL12/CXCR4, Notch, Wnt) support survival and quiescence of malignant clones.	Provides a protective niche, reduces early symptom manifestation, and influences therapy resistance.
Immune Evasion	Malignant clones exploit immune checkpoints and local immunosuppressive mechanisms to avoid detection by cytotoxic lymphocytes.	Contributes to the asymptomatic nature of disease and persistence of occult clones.
Clonal Evolution / Minimal Residual Disease (MRD)	Accumulation of additional genetic hits allows subclinical clones to evolve over time.	Increases risk of progression to overt leukemia or lymphoma; MRD monitoring is critical for prognostic assessment.
Systemic and Microenvironmental Crosstalk	Interactions with cytokines, growth factors, and metabolic cues influence malignant cell behavior.	Modulates proliferation, survival, and potential dissemination, affecting overall disease trajectory.

Clinical Presentation

The clinical presentation of occult hematopoietic malignancies is inherently challenging because these disorders unfold quietly, often without overt symptoms or dramatic laboratory abnormalities. Their early course is shaped by subtle and incremental disruptions in hematopoiesis, immune regulation, or end-organ function, which rarely provoke immediate clinical concern. As a result, many cases surface incidentally during routine health encounters, long before the disease meets diagnostic thresholds for overt leukemia, lymphoma, or plasma cell dyscrasia [17-19]. In most patients, the earliest phase is characterized by complete clinical silence. Individuals feel entirely well, and no specific complaints prompt evaluation. Detection frequently occurs when a full blood count obtained for unrelated reasons reveals mild abnormalities—borderline anemia, slightly elevated lymphocyte counts, or marginal thrombocytopenia. These deviations are often so subtle that they fall within the upper or lower boundaries of normal reference ranges, making them easy to dismiss unless persistent or progressively worsening. Similarly, in plasma cell precursor states such as MGUS or smoldering myeloma, small monoclonal protein spikes may be identified incidentally during screening for neuropathy, chronic kidney disease, or bone pain of uncertain origin [19].

Despite this clinically silent nature, the underlying malignant clone may exert biological effects that manifest as non-specific systemic symptoms. Some patients describe vague fatigue, intermittent malaise, or diminished exercise tolerance—features that reflect low-grade inflammation rather than high tumor burden. Others may experience recurrent mild infections, a signal of early immunologic impairment commonly seen in monoclonal B-cell lymphocytosis or early chronic lymphocytic leukemia. Because these manifestations are nonspecific, they are rarely attributed to an evolving hematologic process without a high index of clinical suspicion [20]. Subtle laboratory findings often provide the earliest measurable clues that an occult malignancy

is present. Mild cytopenias are among the most frequent indicators; macrocytosis, unexplained neutropenia, or borderline thrombocytopenia may herald early myelodysplasia even years before definitive morphologic dysplasia is detectable. Persistent monocytosis can point toward a myeloproliferative or myelodysplastic precursor state, while modestly elevated LDH or β2-microglobulin levels may reflect increased cell turnover in lymphoid or plasma cell clones. The challenge lies in interpreting these findings within clinical context, as similar abnormalities can arise from benign conditions, medication effects, or chronic inflammation [21].

In some cases, organ-specific manifestations precede classical hematologic symptoms. Early lymphoid malignancies may produce subtle lymphadenopathy—small, non-tender lymph nodes that escape notice without systematic examination. Smoldering myeloma or early plasma cell disorders may leave a radiographic footprint long before bone pain develops, such as early vertebral compression fractures, osteopenia, or focal lytic lesions detected on imaging performed for other reasons. Similarly, clonal hematopoiesis may increase systemic inflammation and thrombogenicity, predisposing individuals to cardiovascular events such as myocardial infarction or ischemic stroke even in the absence of overt hematologic disease [22]. As the malignant clone expands, clinical manifestations become more recognizable but may still remain below the diagnostic threshold for an overt malignancy. Patients with early lymphoid disorders may develop slowly progressive lymphocytosis, occasional night sweats, or mild splenomegaly, while those with early myeloid disorders may show increasing frequency of infections, worsening fatigue, or gradually intensifying cytopenias. Plasma cell precursor states may progress to low-grade bone pain, subtle renal dysfunction, or early features of anemia. Yet even in these later phases, many remain clinically stable for extended periods, highlighting the heterogeneity of disease trajectories [23].

Diagnostic Strategies

The diagnosis of occult hematopoietic malignancies is inherently complex because these disorders exist in a biological gray zone, often producing only faint laboratory abnormalities or subtle clinical signals. Unlike overt leukemias or lymphomas, which typically present with conspicuous cytopenias, organomegaly, or constitutional symptoms, occult malignancies require a more nuanced and layered diagnostic approach. This approach integrates careful clinical assessment with advanced laboratory techniques and imaging modalities, allowing clinicians to detect small clonal populations long before they manifest as symptomatic disease [23]. Most diagnostic pathways begin with the incidental identification of mild hematologic abnormalities. A routine full blood count may reveal modest anemia, borderline leukopenia, or thrombocytopenia, while a differential count may uncover persistent lymphocytosis, monocytosis, or eosinophilia. Because these findings often fall within near-normal limits, clinicians must rely on persistence and pattern recognition to distinguish benign variation from early malignant processes. Repeated testing over time is frequently essential, as evolving trends—rather than single abnormal metrics—often provide the first reliable indication of clonal hematopoiesis [24].

Once suspicion is raised, peripheral blood smear evaluation becomes a key early step. Skilled morphologic assessment may reveal subtle dysplastic features such as hypogranulated neutrophils, pseudo–Pelger-Huët cells, small mature lymphocytes with atypical contours, or plasma cell atypia. Although these findings rarely provide a definitive diagnosis, they offer valuable clues that support further investigation [25]. Biochemical studies also play an important role. Elevated LDH, β2-microglobulin, serum free light chain ratio abnormalities, and small monoclonal protein spikes detected on serum protein electrophoresis can suggest early lymphoid or plasma cell disorders. However, these markers are not specific, reinforcing the need for more targeted diagnostic modalities [26]. Flow cytometry has emerged as one of the most powerful tools for detecting occult hematologic malignancies. Modern multiparameter flow cytometry can identify clonal populations at extremely low frequencies—detecting monoclonal B-cell expansions below thresholds required for a diagnosis of chronic lymphocytic leukemia, or revealing aberrant myeloid phenotypes consistent with early myelodysplastic changes. The sensitivity and specificity of this technique make it essential for diagnosing precursor states such as monoclonal B-cell lymphocytosis (MBL) and identifying abnormal blast populations in early myeloid disease [27-28].

In parallel, molecular diagnostics have transformed the landscape of early detection. Next-generation sequencing (NGS) panels allow identification of somatic mutations associated with clonal hematopoiesis, myelodysplasia, or early lymphoid neoplasia. Mutations in genes such as *DNMT3A*, *TET2*, *ASXL1*, *TP53*, *SF3B1*, and *IDH1/2* offer critical insight into clonal behavior, transformation risk, and underlying disease biology. Importantly, the detection of mutations alone does not equate to malignancy; rather, the size of the clone, the variant allele frequency, and the combination of mutations help stratify whether a clonal expansion is benign, indeterminate, or indicative of an evolving malignancy. Thus, molecular testing must always be interpreted in clinical context, ideally by integrating hematologic findings, age, comorbidities, and cytogenetic features [29]. Bone marrow examination remains the gold standard for diagnosing many occult hematopoietic malignancies, especially when cytopenias are unexplained, mutation profiles are concerning, or peripheral blood findings are ambiguous. Bone marrow aspiration and biopsy provide direct assessment of

cellularity, dysplasia, blast percentage, and stromal alterations. Cytogenetic analysis can uncover chromosomal abnormalities such as del(5q), trisomy 12, del(13q), and complex karyotypes, which may define specific disease subtypes or carry prognostic significance. Yet bone marrow evaluation is not always required initially; in many cases, a period of non-invasive surveillance is appropriate before proceeding to invasive diagnostic measures [30].

Imaging modalities are occasionally critical, particularly when lymphoid or plasma cell precursor states are suspected. Low-dose whole-body CT or MRI may detect asymptomatic lytic lesions in smoldering myeloma, while PET-CT may reveal metabolically active lymph nodes or splenic involvement that remain clinically silent. Imaging findings often serve to reclassify a presumed occult disease into an early but clinically important stage, guiding earlier surveillance or intervention (Table 2) [31].

Table 2: Diagnostic Strategies for Occult Hematopoietic Malignancies

Diagnostic Modality	Description / Approach	Sensitivity / Utility	Clinical Relevance
Peripheral Blood Analysis	Complete blood count and peripheral smear to detect cytopenias or subtle morphological changes.	Low–moderate; may miss early clones	First-line, widely accessible; triggers further investigation.
Flow Cytometry / Immunophenotyping	Multiparametric analysis of surface antigens to identify aberrant myeloid or lymphoid populations.	High; detects low-frequency abnormal cells	Allows early detection of occult clones and aids in lineage specification.
Molecular and Genomic Testing	Next-generation sequencing (NGS), targeted gene panels, and digital droplet PCR for mutation detection.	Very high; can detect low allelic burden (<1%)	Identifies clonal mutations, guides MRD monitoring, and informs risk stratification.
Bone Marrow Aspiration and Biopsy	Histopathology, cytogenetics, and molecular analyses of marrow samples.	High; definitive diagnostic method	Confirms clonal architecture, marrow infiltration, and microenvironmental interactions.
Imaging Modalities	PET/CT, MRI to detect marrow infiltration or early lymph node involvement.	Moderate; more sensitive for extramedullary disease	Supports diagnosis when laboratory findings are inconclusive; monitors disease extent.
Minimal Residual Disease (MRD) Assessment	Quantitative PCR, flow cytometry, or NGS to track subclinical clones over time.	Very high; detects clones below conventional thresholds	Predicts progression, guides preemptive therapy, and informs surveillance strategies.

Prognostic Implications

The prognostic landscape of occult hematopoietic malignancies is remarkably heterogeneous, shaped by the interplay between clonal genetics, microenvironmental factors, and host-related variables. Although these disorders are clinically silent at presentation, their long-term implications can be profound. Understanding prognosis in this context requires moving beyond traditional disease classifications to recognize the continuum of clonal behavior that exists between benign hematopoiesis and overt malignancy [32]. One of the most critical determinants of prognosis is the inherent biological risk of malignant transformation. Precursor states such as clonal hematopoiesis of indeterminate potential (CHIP), monoclonal B-cell lymphocytosis (MBL), monoclonal gammopathy of undetermined significance (MGUS), and idiopathic cytopenias of undetermined significance (ICUS) each carry distinctive annual transformation rates, yet even these averages conceal substantial inter-individual variability. For example, CHIP confers a modest overall risk of progression to myeloid malignancy, estimated at roughly 0.5–1% per year, but this risk increases several-fold in individuals harboring high-risk mutations such as *TP53*, *IDH1/2*, or *RUNX1*. Similarly, MGUS carries a 1% per year risk of progression to multiple myeloma, but patients with non-IgG subtype, high M-protein levels, or abnormal free light chain ratios may progress more rapidly. Thus, genetic and biochemical markers serve as key predictors of disease evolution, allowing clinicians to stratify individuals into low-, intermediate-, or high-risk categories [33-34].

Beyond the risk of transformation, occult hematopoietic malignancies also confer significant non-malignant morbidity. Clonal hematopoiesis, for instance, is increasingly recognized as an independent risk factor for cardiovascular disease, accelerating atherosclerosis and predisposing individuals to myocardial infarction, ischemic stroke, and heart failure. This occurs through pro-inflammatory pathways driven by mutant hematopoietic clones, illustrating that clonal disorders can exert systemic effects that are clinically meaningful even without progression to leukemia or lymphoma. Similarly, patients with MBL or early CLL-like clones experience variable degrees of immune dysfunction, resulting in heightened susceptibility to infections long

before overt lymphoid malignancy becomes apparent [35]. Moreover, certain precursor states may compromise organ integrity in ways that mimic or precede overt malignant disease. Smoldering myeloma, for example, can lead to early skeletal fragility, subtle renal dysfunction, or chronic anemia even in the absence of diagnostic criteria for symptomatic myeloma. These early complications highlight the need for vigilance, as they serve as both prognostic indicators and early warning signs that intervention may soon become necessary [36].

Importantly, host characteristics profoundly influence prognosis. Advanced age, chronic inflammatory conditions, metabolic disorders, and immunosenescence can accelerate clonal expansion and increase the likelihood of progression. The convergence of clonal biology with age-related marrow vulnerability explains why occult malignancies are increasingly recognized in older adults and why their clinical consequences extend beyond hematologic transformation alone [37]. The evolving array of molecular diagnostics has refined prognostication further by identifying mutation patterns that predict aggressive behavior. High variant allele frequencies, co-occurrence of multiple driver mutations, and chromosomal abnormalities such as complex karyotypes or del(17p) serve as strong predictors of early progression. Yet the presence of such abnormalities does not mandate immediate treatment; instead, it reinforces the need for tailored surveillance strategies that align monitoring intensity with individual risk [38-39].

CONCLUSION

Occult hematopoietic malignancies represent a critical yet often overlooked dimension of modern hematology, existing within a biologic continuum that bridges benign clonal states and overt malignant disease. Although these conditions frequently present without symptoms and are discovered incidentally, their clinical significance is far from trivial. The silent evolution of small clonal populations reflects intricate interactions between somatic mutations, microenvironmental pressures, and host factors that ultimately determine whether a clone remains stable, progresses slowly, or transforms into aggressive hematologic cancer.

Advances in molecular diagnostics, flow cytometry, and imaging have dramatically enhanced the ability to detect these early disease states, but they have also introduced new challenges in interpretation and management. Understanding the prognostic implications of clonal size, mutation profile, and clinical context is essential for distinguishing low-risk, indolent clones from those that pose meaningful risks of malignant transformation or systemic complications. Increasing evidence demonstrates that even without progression, many occult malignancies exert measurable impacts on cardiovascular health, immune function, bone integrity, and overall physiological resilience.

Conflicts of Interest

The authors declare no conflict of interest

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REFERENCES

1. von Beck K, von Beck T, Ferrell PB Jr, Bick AG, Kishtagari A. (2023). Lymphoid clonal hematopoiesis: implications for malignancy, immunity, and treatment. *Blood Cancer J. 13*(1):5. doi: 10.1038/s41408-022-00773-8.
2. Taylor J, Xiao W, Abdel-Wahab O. (2017). Diagnosis and classification of hematologic malignancies on the basis of genetics. Blood, 130(4):410-423. doi: 10.1182/blood-2017-02-734541.
3. Kontandreopoulou, C. N., Kalopisis, K., Viniou, N. A., & Diamantopoulos, P. (2022). The genetics of myelodysplastic syndromes and the opportunities for tailored treatments. *Frontiers in Oncology*, *12*, 989483.. doi: 10.3389/fonc.2022.989483.
4. Yuan, S., Almagro, J., & Fuchs, E. (2024). Beyond genetics: driving cancer with the tumour microenvironment behind the wheel. *Nature Reviews Cancer*, *24*(4), 274-286.. doi: 10.1038/s41568-023-00660-9.
5. Leoni, S., Ferraresi, M., Motta, I., Hu, C., Fracanzani, A. L., Barcellini, W., & Fattizzo, B. (2024). Deciphering cytopenias in internal medicine: a single-center observational study. *Internal and Emergency Medicine*, *19*(3), 661-668.. doi: 10.1007/s11739-023-03517-z.
6. Hudu, S. A., Alshrari, A. S., Abu-Shoura, E. A. J. I., Osman, A., & Jimoh, A. O. (2025). A critical review of the prospect of integrating artificial intelligence in infectious disease diagnosis and prognosis. *Interdisciplinary Perspectives on Infectious Diseases*, *2025*(1), 6816002. doi: 10.1155/ipid/6816002.
7. Gala, D., Behl, H., Shah, M., & Makaryus, A. N. (2024, February). The role of artificial intelligence in improving patient outcomes and future of healthcare delivery in cardiology: a narrative review of the literature. In *Healthcare* (Vol. 12, No. 4, p. 481). MDPI. doi: 10.3390/healthcare12040481.
8. Hu, D., & Shilatifard, A. (2016). Epigenetics of hematopoiesis and hematological malignancies. *Genes & development*, *30*(18), 2021-2041. doi: 10.1101/gad.284109.116.
9. Ntziachristos, P., Abdel-Wahab, O., & Aifantis, I. (2016). Emerging concepts of epigenetic dysregulation in hematological

malignancies. *Nature immunology*, *17*(9), 1016-1024. doi: 10.1038/ni.3517.
10. Cobo, I., Tanaka, T., Glass, C. K., & Yeang, C. (2022). Clonal hematopoiesis driven by DNMT3A and TET2 mutations: role in monocyte and macrophage biology and atherosclerotic cardiovascular disease. *Current opinion in hematology*, *29*(1), 1-7. doi: 10.1097/MOH.0000000000000688.
11. Sato, N., Goyama, S., & Kitamura, T. (2025). ASXL1 mutation-related clonal hematopoiesis and age-related diseases: clinical evidence and molecular insights. *International Journal of Hematology*, *122*(3), 327-340. doi: 10.1007/s12185-025-04038-5.
12. Tomasoni, C., Pievani, A., Rambaldi, B., Biondi, A., & Serafini, M. (2023). A question of frame: the role of the bone marrow stromal niche in myeloid malignancies. *Hemasphere*, *7*(6), e896. doi: 10.1097/HS9.0000000000000896.
13. Tufail, M., Jiang, C. H., & Li, N. (2025). Immune evasion in cancer: mechanisms and cutting-edge therapeutic approaches. *Signal transduction and targeted therapy*, *10*(1), 227.doi: 10.1038/s41392-025-02280-1.
14. Mejía-Guarnizo, L. V., Monroy-Camacho, P. S., Turizo-Smith, A. D., & Rodríguez-García, J. A. (2023). The role of immune checkpoints in antitumor response: a potential antitumor immunotherapy. *Frontiers in Immunology*, *14*, 1298571. doi: 10.3389/fimmu.2023.1298571.
15. Zhu, L., Xu, R., Yang, L., Shi, W., Zhang, Y., Liu, J., ... & Bing, P. (2023). Minimal residual disease (MRD) detection in solid tumors using circulating tumor DNA: a systematic review. *Frontiers in Genetics*, *14*, 1172108. doi: 10.3389/fgene.2023.1172108.
16. Aguilar-Cazares, D., Chavez-Dominguez, R., Marroquin-Muciño, M., Perez-Medina, M., Benito-Lopez, J. J., Camarena, A., ... & Lopez-Gonzalez, J. S. (2022). The systemic-level repercussions of cancer-associated inflammation mediators produced in the tumor microenvironment. *Frontiers in endocrinology*, *13*, 929572. doi: 10.3389/fendo.2022.929572.
17. Hu, D., & Shilatifard, A. (2016). Epigenetics of hematopoiesis and hematological malignancies. *Genes & development*, *30*(18), 2021-2041. doi: 10.1101/gad.284109.116.
18. Cheng, H., Sun, G., & Cheng, T. (2018). Hematopoiesis and microenvironment in hematological malignancies. *Cell Regeneration*, *7*(1), 22-26. doi: 10.1016/j.cr.2018.08.002.
19. Caiado, F., & Manz, M. G. (2025). Clonal hematopoiesis: impact on health and disease. *Hematological oncology*, *43*, e70075. doi: 10.1002/hon.70075.
20. Bower, J. E., & Lamkin, D. M. (2013). Inflammation and cancer-related fatigue: mechanisms, contributing factors, and treatment implications. *Brain, behavior, and immunity*, *30*, S48-S57. doi: 10.1016/j.bbi.2012.06.011.
21. Oster, H. S., & Mittelman, M. (2024). How we diagnose Myelodysplastic syndromes. *Frontiers in Oncology*, *14*, 1415101. doi: 10.3389/fonc.2024.1415101.
22. Ganapathi, K. A., Pittaluga, S., Odejide, O. O., Freedman, A. S., & Jaffe, E. S. (2014). Early lymphoid lesions: conceptual, diagnostic and clinical challenges. *haematologica*, *99*(9), 1421-32. doi: 10.3324/haematol.2014.107938.
23. Munir, F., Hardit, V., Sheikh, I. N., AlQahtani, S., He, J., Cuglievan, B., ... & Khazal, S. (2023). Classical Hodgkin lymphoma: from past to future—a comprehensive review of pathophysiology and therapeutic advances. *International journal of molecular sciences*, *24*(12), 10095. doi: 10.3390/ijms241210095.
24. Tefferi A, Hanson CA, Inwards DJ. (2005). How to interpret and pursue an abnormal complete blood cell count in adults. *Mayo Clin Proc. 80*(7):923-36. doi: 10.4065/80.7.923.
25. Ayan, M. S., Abdelrahman, A. A. M., Khanal, N., Elsallabi, O. S., & Birch, N. C. (2015). Case of acquired or pseudo-Pelger-Huët anomaly. *Oxford Medical Case Reports*, *2015*(4), 248-250. doi: 10.1093/omcr/omv025.
26. Tripathy, S. (2012). The role of serum protein electrophoresis in the detection of multiple myeloma: an experience of a corporate hospital. *Journal of clinical and diagnostic research: JCDR*, *6*(9), 1458-61. doi: 10.7860/JCDR/2012/4213.2532.
27. Carulli, G., Ottaviano, V., Guerri, V., Giuntini, S., Sammuri, P., Ciancia, E. M., & Azzarà, A. (2014). Multiparameter flow cytometry to detect hematogones and to assess B-lymphocyte clonality in bone marrow samples from patients with non-Hodgkin lymphomas. *Hematology Reports*, *6*(2), 5381.. doi: 10.4081/hr.2014.5381.
28. Holl, E., Kapinsky, M., & Larbi, A. (2025). An update on flow cytometry analysis of hematological malignancies: focus on standardization. *Cancers*, *17*(12), 2045.. doi: 10.3390/cancers17122045.
29. Chatterjee, G., He, R., Patkar, N., Viswanatha, D., & Langerak, A. W. (2025). Molecular techniques in haematopathology: what and how?. *Histopathology*, *86*(1), 38-57. doi: 10.1111/his.15332.
30. Tshabalala WS, Pillay S, Wilson DPK. (2020). Diagnostic outcomes of bone marrow aspirate and trephine biopsies performed at a hospital in KwaZulu-Natal, South Africa. *Afr J Lab Med.,9*(1):1028. doi: 10.4102/ajlm. v9i1.1028.
31. Derlin, T., & Bannas, P. (2014). Imaging of multiple myeloma: Current concepts. *World journal of orthopedics*, *5*(3), 272-82. doi: 10.5312/wjo. v5.i3.272.

32. Zhang, Q., Yim, R., Lee, P., Chin, L., Li, V., & Gill, H. (2024). Implications of clonal hematopoiesis in hematological and non-hematological disorders. *Cancers*, *16*(23), 4118. doi: 10.3390/cancers16234118.
33. Boddicker, N. J., Shanafelt, T. D., Parikh, S. A., Rabe, K. G., Griffin, R., Norman, A. D., ... & Slager, S. L. (2025). CHIP amplifies the risk of lymphoid malignancies in individuals with monoclonal B-cell lymphocytosis (MBL). *Blood cancer journal*, *15*(1), 195. doi: 10.1038/s41408-025-01385-8.
34. Steensma DP, Bejar R, Jaiswal S, Lindsley RC, Sekeres MA, Hasserjian RP, Ebert BL. Clonal hematopoiesis of indeterminate potential and its distinction from myelodysplastic syndromes. Blood. 2015;126(1):9-16. doi: 10.1182/blood-2015-03-631747.
35. Evans MA, Walsh K. Clonal Hematopoiesis in Cancer and Cardiovascular Disease: JACC: CardioOncology State-of-the-Art Review. JACC CardioOncol. 2025;7(5):470-495. doi: 10.1016/j.jaccao.2025.06.006.
36. Waxman AJ, Kuehl M, Balakumaran A, Weiss B, Landgren O. Smoldering (asymptomatic) multiple myeloma: revisiting the clinical dilemma and looking into the future. Clin Lymphoma Myeloma Leuk. 2010;10(4):248-57. doi: 10.3816/CLML.2010. n.053.
37. Barbé-Tuana F, Funchal G, Schmitz CRR, Maurmann RM, Bauer ME. The interplay between immunosenescence and age-related diseases. Semin Immunopathol. 2020;42(5):545-557. doi: 10.1007/s00281-020-00806-z.
38. Pratiwi L, Mashudi FH, Ningtyas MC, Sutanto H, Romadhon PZ. Genetic Profiling of Acute and Chronic Leukemia via Next-Generation Sequencing: Current Insights and Future Perspectives. Hematol Rep. 2025;17(2):18. doi: 10.3390/hematolrep17020018.
39. Obeagu EI. Early detection and better outcomes: molecular approaches in pediatric hematologic malignancies - a review. Ann Med Surg (Lond). 2025;87(10):6564-6573. doi: 10.1097/MS9.0000000000003723.